Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY,
HARVARD UNIVERSITY.

DISPERSION IN ELECTRIC DOUBLE REFRACTION.

By Howard Lane Blackwell.

Presented by John Trowbridge, April 8, 1905. Received December 31, 1905.

The object in the following paper is to present a study of dispersion in the electric double refraction of carbon bisulphide; for though as many as fourteen observers have experimented with electric double refraction since its discovery thirty years ago, even the existence of dispersion in the phenomenon has been unnoticed by all except two. Only one of them made any suggestion as to what function of the wave-length represents the double refraction, and the function which he suggested turns out not to hold even in the visible spectrum. The departure from it is important both in the direction of electro-magnetic waves and towards the ultra-violet.

When a condenser is charged, the dielectric becomes doubly refracting. Under the influence of the electric field it acquires the optical property of a uniaxial crystal. Electric double refraction has been induced in glass, resin, and other transparent solids, and in over one hundred insulating liquids. Even conducting liquids, — water, nitrobenzol, and others, — are capable of exhibiting this effect, though only for an instant. Solid insulators, like glass, require a number of seconds after the field is established to acquire the new property most strongly. In liquids, however, the change is sensibly instantaneous. Moreover, just as natural uniaxial crystals fall into two classes, positive and negative, so substances rendered doubly refracting by the electric field behave some of them like positive, some like negative crystals. In other words, the velocity of the extraordinary wave is increased over that of the ordinary in some substances and decreased in others. Carbon bisulphide becomes positively uniaxial and exhibits electric double refraction more strongly than almost any other liquid tried.

The first investigation in this general field was an unsuccessful attempt by Faraday in 1834 to discover some effect of electrostatic strain on the propagation of light.[1] The first successful experiment was the discovery of the effect by Kerr in 1875, and in an admirable series of papers extending over nearly twenty years, he continued to contribute to the advance in this new field.[2] Other investigators, following Kerr, are: Gordon,[3] Mackenzie,[4] Roentgen,[5] Grunmach,[6] Blondlot,[7] Brongersma,[8] Kundt,[9] Quincke,[10] Lemoine,[11] Abraham,[12] Schmidt,[13] and Elmén.[14]

Even after Kerr's discovery, Mackenzie, Grunmach, and Gordon in his first attempt, failed to observe electric double refraction. Gordon in his second attempt, and Brongersma confirmed Kerr's discovery. Roentgen added new liquids to Kerr's list, and studied the electric double refraction of quartz. Kundt observed quartz only.

The first quantitative observations were made by Kerr, who showed (with white light, but with great care) that the double refraction of carbon bisulphide varies as the square of the strength of electric field. In 1883 Quincke undertook to determine the coefficient of proportionality between double refraction and field-strength. He worked partly with white light and partly with light from a red color screen, but did not mention dispersion, and his results do not show it. Lemoine in 1896 redetermined this coefficient, which Quincke called "B," for carbon bisulphide, with a red color screen, but gave no data and few details to show the accuracy of his result. Elmén, working with Brace, in 1904, observed "B" in very weak electric fields. None of them noted dispersion.

It was left for Kerr in 1892 to show the existence of dispersion in the phenomenon he had discovered and studied so successfully. He did not multiply observations on his latest discovery, however, but inferred from what seem scanty data, that in carbon bisulphide the double refraction "varies exactly, or very nearly" inversely as the square-root of the wave-length. The only other observer who noticed dispersion is Schmidt. In 1901 he published observations of the amount of electric double refraction in a number of organic liquids compared with that in carbon bisulphide as standard. His observations were made with blue and with red light obtained with color screens (light of wave-lengths "$490 \mu\mu$" and "$680\ \mu\mu$"), and with what he called the "blue-violet transition tint ($\lambda = 580\ \mu\mu$)," obtained apparently by rotating the Nicols. He expressed the electric double refraction of the substance under investigation in terms of the effect in carbon bisulphide. It thus does not appear whether his data indicate dispersion in the liquid under observation, or in the carbon bisulphide used for comparison, but merely that in one or other, or both, there is dispersion. The reduction of his observations to absolute value would depend on the determinations of "B" in carbon bisulphide made by Quincke and by Lemoine, neither of whom noted the variation of "B" with variation of wave-length.

---

[1] Experimental Researches in Electricity, Series VIII, §§ 951–955 (April, 1834).

[2] Phil. Mag., (4) **50**, 337, 446 (1875); (5) **8**, 85, 229 (1879); **9**, 157 (1880); **13**, 153, 248 (1882); **20**, 363 (1885); **37**, 380 (1894); **38**, 144 (1894); Rep. Brit. Ass'n, Edinb., 157 (1892).

[3] Phil. Mag., (5) **2**, 203 (1876); Treat. on Elec. & Mag., **11**, 247 (1880).

[4] Wied. Ann., **2**, 356 (1877).

[5] Wied. Ann., **10**, 77 (1880); **18**, 213 (1882); **19**, 319 (1882).

[6] Wied. Ann., **14**, 110 (1881).

[7] Jour. de Phys., (2) **1**, 364 (1882); Compt. rend., **106**, 349 (1888).

[8] Wied. Ann., **16**, 222 (1882); Ann. d. Phys., **7**, 708 (1883).

[9] Wied. Ann., **18**, 228 (1882).

[10] Wied. Ann., **19**, 729 (1883).

[11] Compt. Rend., **122**, 835 (1896).

[12] Jour. de Phys., (3) **9**, 265 (1900).

[13] Ann. d. Phys., (4) **7**, 142 (1901).

[14] Phys. Rev., **20**, 54 (1905).

In short, Kerr's measurements on the variation of electric double refraction with variation in wave-length furnish the only suggestion thus far as to the law of dispersion.

NEW RESULTS.

In the eight experiments whose results are given below, the temperature remained constant near 11° in five, and near 24° in the other three. The field-strength during each of the experiments was also very nearly constant, and differed little from experiment to experiment. The results are given for a potential gradient of 56,000 volts per centimeter. The observed double refraction, or separation δ, is proportional to the difference between the ordinary and electrically produced extraordinary indices of the liquid, $(\mu_\epsilon - \mu_\omega)$. This quantity is the separation in centimeters introduced between the mutually perpendicular components of a wave of plane-polarized light in traversing one centimeter of the substance in question, — in this case carbon bisulphide, — at a certain temperature, in a field of certain strength. The double refraction of natural uniaxial crystals is usually similarly expressed as the difference between the two indices. Accordingly, the present observations are expressed in terms of this characteristic difference. Its values are given in Table I, and plotted in Figure 1, in per cent of its value at 24°.0 at wave-length 5890. This value, the factor reducing the values of Table I to absolute index of refraction, is found in these experiments to be about $7.04 \cdot 10^{-7}$.

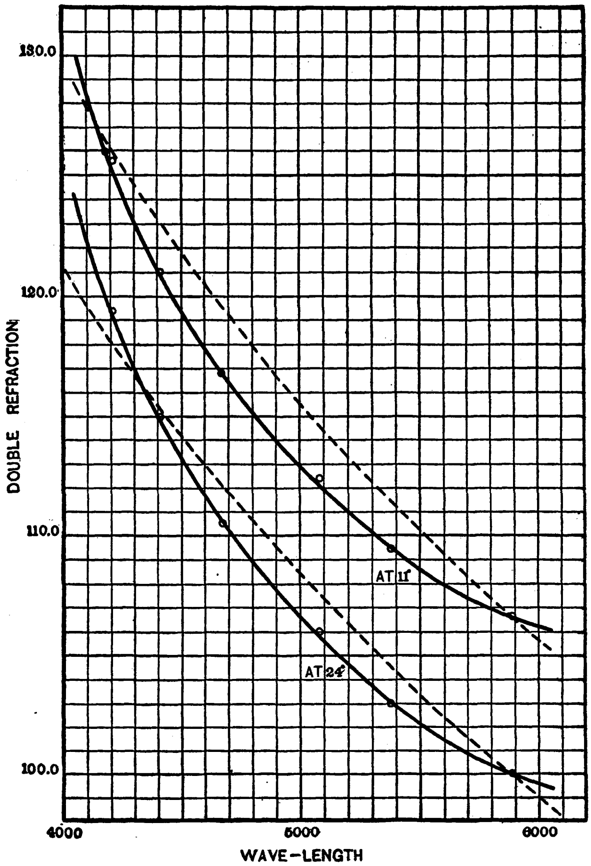

FIGURE 1. ELECTRIC DOUBLE REFRACTION OF CARBON BISULPHIDE.

The heavy curves show the double refraction observed with carbon bisulphide at 11° and at 24°. The dotted curves show how the double refraction was previously supposed to vary, — inversely as the square-root of wave-length. The departure of each observed curve from the dotted one is important, for the dotted curve is an equilateral hyperbola approaching the axes of zero wave-length and zero double refraction as asymptotes, whilst the observed curve rises much more sharply towards the edge of strong absorption in the ultra-violet, and falls much more slowly than the hyperbola towards the red.

The wave-length is expressed in 10^{-10} meters; the double refraction is expressed in per cent of the value of $(\mu_\epsilon - \mu_\omega)$ at 24°.0 with sodium light, — equal to about $7.04 \cdot 10^{-7}$; the field-strength giving these values is 56,000 volts per cm.

TABLE I.

ELECTRIC DOUBLE REFRACTION OF CARBON BISULPHIDE

Experiment.	Conditions under which observations were made:		Double refraction, reduced to 24°.0 and 11°.0 as standard temperatures, and 8990 volts (= 56,000 volts per cm.) the value at λ = 5890 being taken as 100 at each standard temperature:							
No.	Volts.	Temp. of CS_2.	Standard Temp.	λ 4180	λ 4216	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890
1	9000?	24°.3	24°.0		120.2	115.5	111.2	106.1	103.2	100.0
4	8980	25°.9	"	118.9		114.1	110.9	105.9	103.1	"
8	8890	22°.5	"		118.5	114.4	109.5	105.9	102.7	"
Mean (plotted in Fig. 1).			24°.0	(118.9)	119.4	115.0	110.5	106.0	103.0	100.0
2	8800?	9°.2	11°.0	119.2	118.0	112.9	109.2	105.4		100.0
3	8885	10°.9	"	118.9		114.3	110.9	106.9	103.7	"
5	9105	11°.9	"	116.1		112.2	108.9	104.9	101.9	"
6	9150	11°.0	"	117.9	117.3	113.8	109.3	105.3	102.5	"
7	8990	10°.4	"	118.9	118.2	114.1	110.2	105.7	103.0	"
Mean			11°.0	118.2	117.8	113.5	109.7	105.6	102.8	100.0
Mean at 11°.0 expressed in per cent of value taken as 100 at 24°.0 and λ = 5890 (plotted in Fig. 1).				126.0	125.6	121.0	116.8	112.4	109.4	106.6

Absolute values are obtained in terms of $(\mu_\epsilon - \mu_\omega)$ by multiplying the above values by $7.04 \cdot 10^{-7}$, the observed absolute value of the double refraction at 24°.0 and λ = 5890.

Observations were terminated in the violet by the absorption of the liquid. The sharpness with which absorption begins is shown in the photograph of the iron spectrum taken through 96 cm. of carbon bisulphide. (Plate, Figure A.) At wave-length 4180 the spectrum was still bright; at 4144 very faint. Within 50 Ångström units change of wave-length the light was practically cut off. In the following observations on dispersion the light passed through 109 cm. of liquid, and measurements of the photographs could not be made on account of the absorption beyond wave-length 4180, a point near the limit of the violet.

As this sharply bounded region of total absorption is approached, the dispersion varies rapidly. According to the law suggested by Kerr, the double refraction should increase as the inverse square-root of the wave-length. This curve is an equilateral hyperbola whose axes are the axes of co-ordinates. It is shown dotted in Figure 1. Each hyperbola was calculated by starting with the observed value of the double refraction for the given temperature at wave-length 5890. But the curve of double refraction observed in the present experiments is much steeper than the hyperbola suggested by Kerr, as the region of total absorption is approached. This raises the question whether ***the approach to an absorption band*** may not be the controlling factor rather than the change of wave-length.

The possible effect of an absorption band is briefly considered mathematically by Néculcèa,[15] in his summary of the mathematical papers on the general phenomenon of electric double refraction by Pockels,[16] and Voigt.[17]

METHOD.

A means of measuring double refraction, and at the same time of taking into account the dispersion, is furnished by Babinet's compensator.

When this is viewed by plane-polarized light and an analyzing Nicol, both properly oriented, a symmetrical system of straight dark fringes appears, of which the central one is achromatic. If a doubly refracting body, also properly oriented, be introduced between the compensator and the source of light, the fringes are shifted through a distance x, proportional to the double refraction. By analyzing the dark central fringe with a spectroscope whose slit cuts the fringe at right angles, a spectrum is formed traversed by a dark band, and any variation in x with variation in color is made evident. If the dispersion of double refraction in the material under observation be the same as that of the compensator, namely of quartz, the straight dark band in the spectrum will shift parallel to itself. If the dispersion be different from that of quartz, the shifted band will be a curve plotting the difference. By the use of a camera and orthochromatic plates in place of the usual observing telescope permanent records may be obtained. This is an advantage, because measurements of the negatives can be made at leisure more accurately than visual observations under the pressure of experiment.

---

[15] Le Phénomène de Kerr, p. 60. (Par E. Néculcèa; C. Naud, Éditeur; Paris, 1902.)

[16] Gött. Nachr. Math. Phys. Klasse, **2**, 102 (1896).

[17] Wied. Ann., **69**, 297 (1899); Ann. d. Phys. (Jan., 1901).

APPARATUS.

Accurate measurement of double refraction in a strong electric field requires above all a source of constant electromotive force. The Jefferson Physical Laboratory is especially well fitted for such work in having a storage battery of twenty thousand cells.

Electrodes. — The success of the method depends upon the constancy and uniformity of the electric field. Plane, parallel electrodes are necessary to secure uniformity, and the distance between them must be everywhere the same, and accurately known. In order to reduce the voltage required to produce a given strength of field, the distance, " *a*, " between the bars was made only 0.1607 cm. Since the field-strength is the difference of potential divided by this distance, and enters the expression for the double refraction as the square, the percentage error of " *a* " is doubled in the result. To keep the error in distance between electrodes negligible, the electrodes were made of silver deposited in a thin bright film on two heavy glass bars whose faces were prepared at the optical works of the Alvan Clark & Sons Corporation. The Newton's fringes formed when a plane test-plate was placed anywhere on these surfaces before they were silvered showed them to be far more nearly plane than

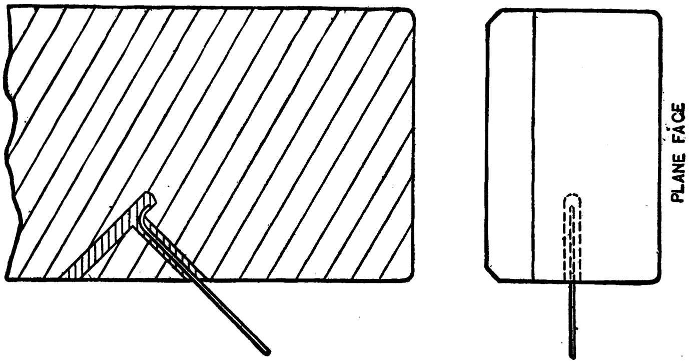

FIGURE 2. Section and end view, actual size, of silvered glass bar used as electrode, showing method of connecting to silver film. The film extends from the plane face around the corners and up the sides higher than the wire.

necessary to equal the accuracy obtainable with the optical parts of the apparatus.

The bars are rectangular, 2.3 cm. thick, with faces 3.6 cm. wide by 96.0 cm. long. The edges and corners are smoothly rounded to a radius of something over one millimeter so that the plane silver films on the faces do not end in edges which might determine spark discharge, but round back on the sides of the bars. Solid electrical connection with the films is made through two pairs of small intersecting holes drilled in each bar on opposite sides near one end (Figure 2). A silver wire is clinched in one hole of each pair and both holes are then filled with the spongy gold used in dentistry firmly tamped in. When the bar is silvered the film comes down perfectly solid and continuous over the glass and the gold, and even if the film should break away from the wire where the latter enters the bar, still through the other filled hole the electrical connection would remain perfect. Reflection from the silver film was always improved by careful dry polishing with settled rouge on washed chamois. Minute scratches are produced, but the gain in reflected light when the bars are in use close together, face to face, is important.

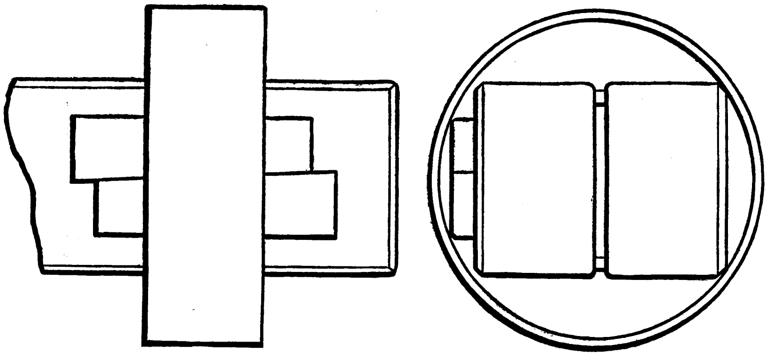

Figure 3. Silvered glass bars wedged face to face. Side view and end view, showing ring, wedges, and little quartz pieces separating bars.

To hold the bars rigidly at a constant accurately known distance apart small flat pieces of quartz are placed between them close to each edge about every eight centimeters. These pieces of quartz were all cut from the same plate which had been ground and polished at the Clarks' more closely plane and uniform in thickness than a tenth of one per cent of the total thickness which is 1.607 mm. Similar spacer pieces of glass were previously used, but their insulating power seemed in time to fail. The bars are finally firmly wedged together in glass rings just large enough to slip over them (Figure 3). Thus assembled, they are shown in the Plate, Figure B.

Tube. — The construction of the tube to hold these bars immersed in the liquid to be observed was a difficult problem. The tube must admit insulated leads to the bars from a source of high voltage, must be closed liquid tight by glass end-plates, must be connected by glass tubes with a supply of pure, dry carbon bisulphide, and must be chemically inert and capable of being made chemically clean. It must be three inches in diameter and nearly four feet long (7 × 110 cm.).

Glass tubes were tried first. Four in succession cracked spontaneously. Apparently such large tubes are under great internal strain, and when this is released in grinding the ends, the glass gradually yields. Sometimes a night and sometimes a week elapsed before the crack came, but fortunately it came before any tube was in place and filled with carbon bisulphide.

Glass is too dangerous to rely on, and special enamelled iron tubes were tried. On opposite sides, as near as possible to each end, insulating " lava " bushings about 2.5 cm. in diameter were screwed in before enamelling. The ends of the tubes were flanged, and had to be machined to a smoothly convex surface in order to retain a good continuous coating of enamel. Four attempts were made before a satisfactory tube was secured.

Closing Tube. — The necessity of having enamel on the ends of the tube is due to the method of closing it. In order to avoid the use of washers, or cement, which might be more or less soluble in carbon bisulphide, a fine fit alone is relied upon. Glass discs for the ends were cut out of " crystal plate," about 1.5 mm. thick, only those being used which when finished seemed free from double refraction. " Crystal plate " is ground and polished in manufacture, and consequently free from small irregularities in the surface. This was shown with an optically flat test-plate by the smoothness of the Newton's fringes in the air film between plate and disc. The enamelled ends of the tube were ground, at the Clarks', optically flat and nearly parallel. The tube was then closed by simply pressing the glass plates against the flat ends (Figure 4). Thin rubber rings were inserted between the glass and the rigid cast-iron rings as a precaution against breakage.

When all is in place, a continuous rubber ring, or gasket, previously slipped over the tube, is wired down on tube and ring, and mercury is poured into the annular space between, through a small hole in the iron ring. This makes the ends air tight, so that the tube can be exhausted and the liquid drawn in without any moist or dusty outside air.

Connections. — Ground joints in the enamelled lava bushings admit the side-tubes connecting with the supply of carbon bisulphide and with a filter-pump. A three-way glass stopcock permits the exhaust to be closed and air to be admitted through drying tubes of phosphoric pentoxide when the liquid used in the observing tube is to be run back into its reservoir. The battery connections are made through platinum wires sealed into glass stoppers ground to fit the other lava bushings, and all these connections are also mercury-sealed.

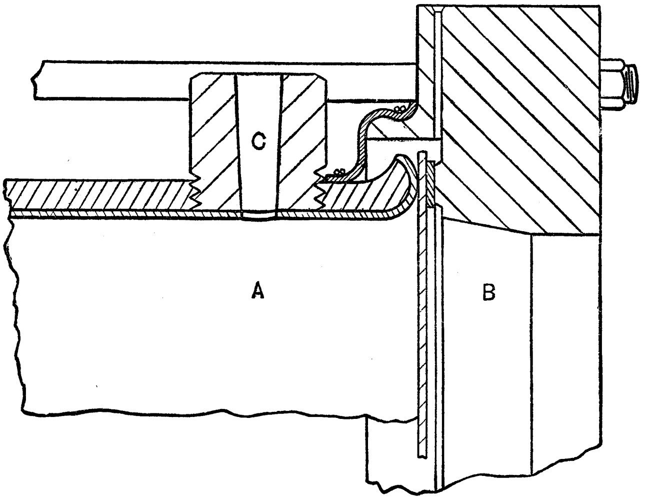

FIGURE 4. SECTION OF THE TUBE SHOWING METHOD OF CLOSING ENDS.

A, Tube in longitudinal section, with glass plate against right-hand end.

B, Cast-iron ring bolted against end, pressing rubber ring, shown in section, against glass plate. Notice small vertical duct in ring through which mercury is poured in to fill annular space enclosed around edge of glass plate by rubber ring shown in section as wired down to flange of iron ring and to tube.

C, "Lava" bushing, hollow, for side tube admitting liquid and electrical connection to electrodes in tube.

Advantage is taken of two of these side outlets to insert permanently, at the upper and lower ends of the tube, two small mercury thermometers which can be read through the glass side-tubes.

OPTICAL PARTS.

The principal parts of the illuminating system are an arc lamp, short focus objective, and Nicol prism. The arc lamp is entirely enclosed in a sheet-iron case into which cool air from another room is forced by a fan. This precaution is taken against fire, so that if the carbon bisulphide should by any chance leak, the heavy vapor could not creep into the lantern and explode. The arc-circuit switch is opened under oil. Since the vapor of carbon bisulphide ignites very much below red heat a water cell is placed in front of the condensing lens of the lantern, so that the slit which is at the focus cannot become hot enough to ignite the inflammable vapor in case of a leak. A half-inch microscope objective sends a bright, thin, very little divergent beam from the slit through the polarizing Nicol and up the tube.

The Babinet's compensator is fastened to the face of the spectroscope slit, behind which, in the collimating tube, is the analyzing Nicol. A direct-vision prism-train receives the light, and a camera with long focus achromatic objective takes the place of the observing telescope.

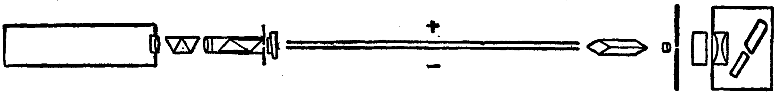

FIGURE 5. ARRANGEMENT OF APPARATUS.

A half-inch objective is used to send a strong beam of polarized light through the carbon bisulphide.

The tube containing the electrodes and liquid is mounted sloping, in order that air bubbles may not lodge under the spacer pins between the bars during filling and cause spark discharge later. The arrangement of apparatus is shown in Figure 5.

The amount of double refraction due to ether drift, if there is such an effect, is less than $10^{-8}\ \mu_\omega$ according to Lord Rayleigh,[18] and the values of the electric double refraction obtained in the present experiments are not less than $70 \cdot 10^{-8}\mu_\omega = (\mu_e - \mu_\omega)$, so that they cannot be affected by more than 1.5 per cent. But if the effect of ether drift should turn out not to be negligible the position of the tube should be known. It is nearly in the magnetic meridian, and slopes down to the north about 23° from horizontal.

---

[18] Phil. Mag., 4, 678–683 (Dec., 1902).

Electrical Apparatus.

In determining the strength of the electric field, since the double refraction varies as the *square* of the field-strength, it is necessary to measure the difference of potential with a percentage error less than *one half* that of the optical measurements. With differences of potential as high as ten thousand volts and higher, the readings of electrometers depend to an uncertain extent on the condition of the air, especially on the humidity, and it seemed preferable to use a high-resistance potentiometer and Clarks' standard cell.

Potentiometer. — To extend the range of the Crompton potentiometer to fifteen thousand volts, and still permit readings to an accuracy of one tenth of one per cent, required one million ohms of extension coils with a negligible temperature coefficient and a carrying capacity of fifteen milliamperes continuously.

Special Resistance. — The resistance was therefore built up of ninety coils, each of ten thousand ohms, wound with a single strand of number 37 (B. & S.) double silk-covered, paraffined special resistance wire, on seasoned maple spools. Single winding secures the least possible difference of potential between adjacent turns, and successive layers are separated by paraffined paper. The spools before winding were tested, and none found to have less resistance between opposite sides of the core than 100 megohms. The wound spools were gradually heated in an electric oven to 140° C., and maintained so for about three hours, when they were immediately immersed in melted paraffine also at 140°, and kept hot for three hours more. The spools finally ceased to give off air bubbles, and they were left in the bath while it was gradually allowed to solidify, so that as the cooling paraffine in the spools shrank, air might not penetrate. The bath was then barely melted and the spools withdrawn and dipped once more. In this way dry coils, well insulated and well protected from atmospheric influences, were obtained.

They were mounted in groups of nine on bright hard-rubber and the terminals of each coil were soldered without the use of acid to brass binding posts on hard-rubber strips on opposite sides of the ventilated containing boxes.

The resistance of each coil thus mounted can be measured with a standard bridge. The resistance of the sum can be taken as the sum of these resistances, since the coils and their terminals are so highly insulated from one another.

But since the fall of potential may reach as much as one hundred and fifty volts per coil in use, and the resistance was measured with only six volts, it was an open question whether the increased leakage at the higher voltage between such an enormous number of adjacent turns would be negligible. To settle this question, a d'Arsonval galvanometer was calibrated with a known resistance box and standard cell to read current. The current through each coil of a set of nine was then measured with six volts per coil and with one hundred and fifty. Within the limit of error of the observations, one tenth of one per cent, the current proved proportional to the voltage.

Static Voltmeter. — With this resistance and potentiometer satisfactory measurements of potential up to fifteen thousand volts were obtainable, but another difficulty presented itself. The electromotive force of the battery with the potentiometer connected falls perceptibly in a few seconds, even with the small discharge rate of fifteen milliamperes. An auxiliary static voltmeter calibrated immediately before and after using is necessary. A very simple device has proved exceedingly sensitive. Between two parallel plates of brass about fifteen centimeters square a silvered glass disc is hung, four or five centimeters in diameter, firmly cemented to a small, straight, steel clock spring, thus probably securing nearly perfect elasticity in the moving parts within the limits of deformation. The whole is enclosed in wood and glass. The spring and one plate are connected to one terminal and the other plate to the other terminal of the high voltage line, and deflections can be read by a telescope and micrometer eyepiece to one tenth of one per cent. Moreover, successive calibrations agree to this degree of accuracy.

PURIFICATION OF CS_2.

Though small quantities of impurities often do not preceptibly influence the behavior of a substance, it is more satisfactory to work with a pure substance, or definite mixture. Pure carbon bisulphide can be ordered, but is said to deteriorate in a short time by the formation of more complex sulphides.[19] Kerr, Quincke, and Schmidt all lay stress on the need of freeing the carbon bisulphide from solid particles in order to prevent sparks. It is possible also that traces of dissolved water lower the obtainable difference of potential. Accordingly the following method of purifying and drying CS_2 was used.

(1) To commercial carbon bisulphide add quicklime, stand a day, digest four hours (with return condenser), distil.

---

[19] Berthellot, A. Ch., (7), **14**, 155; **19**, 150.

(2) Stir with plenty of Hg, repeat till fresh Hg is not tarnished. Decant.

(3) Stir with strong aqueous solution of $HgCl_2$ till no more precipitate, remove $HgCl_2$ (separating funnel), keep in dark.

(4) Dry over fused $CaCl_2$ at least a day. Stir. Keep cool and dark.

(5) Decant, add P_2O_5 (resublimed if necessary to remove P), digest for some hours (with return condenser), distil.

In the last step the distillate before condensation was passed through about four feet (120 cm.) of drying tubes filled with phosphoric pentoxide and glass wool, and kept at about 50° C. It was then washed free from any possible particles of pentoxide by bubbling up through some ten inches (25 cm.) of chemically clean glass beads immersed in a portion of the liquid earlier distilled. The pure dry gas was finally condensed and run into the receiving bottle. The bottle had already been connected to the observing tube so that the liquid could be used without exposure to the undried and more or less dusty air of the room. All joints were of ground glass mercury-sealed. The temperature of the vapor during distillation did not vary more than 0°.02 till near the close, when the vapor began to superheat on the warmer walls of the distilling bottle. Carbon bisulphide thus purified is a beautiful, sparkling, colorless, limpid liquid with a pleasant odor suggesting ether. Probably the most delicate test of its purity is its odor. The bad smell of commercial carbon bisulphide is caused by the impurities.

In the purification of this substance in such large quantities as this,—about twelve liters at a time,—every precaution was taken against fire. No flames were used in the room, and the liquid was distilled from a water-bath warmed by an immersed electric heater. Thus there was no object as hot as boiling water, and no spark, which could possibly be reached by any vapor of carbon bisulphide which might escape.

Such are the method and devices developed step by step by actual experience in solving this threefold problem, — optical, electrical, and chemical.

Procedure.

In these measurements the carbon bisulphide was purified as described, but had stood in glass bottles for several months, though in the dark, hermetically sealed, and dry. After the measurements it was examined, and its freedom from disagreeable odor made it seem probable that deterioration had not taken place.

Each observation consisted essentially of three photographs of the spectrum taken on successive strips of the same plate. With everything in adjustment, but with no electric field, the zero band was taken; with the same adjustments the voltage band was taken, with the electric field; and the reference spectrum was secured by temporarily inserting, immediately in front of the compensator, a sodium flame, and then a cadmium spark. The slit was 0.3 mm. broad, but even with such a broad slit the voltage and zero bands each had to be exposed for at least forty minutes. With this breadth of slit, however, the position of any wave-length could be determined with sufficient accuracy, as it affects the results only as the square-root approximately. A typical photograph is shown in the Plate, Figure C. During the exposure of the voltage band, readings of the potential were taken nearly every minute. Immediately before and after taking a voltage band the static voltmeter was calibrated with the potentiometer and one of three concordant Clark's standard cells. In the worst case the calibration curves differed by four tenths of one per cent, and generally they coincided.

But the measurement of the negatives proved slower and more troublesome than securing them. Each negative was mounted in front of ground glass illuminated by transmitted light, and was measured with a telescope sliding on a vertical scale. In the focal plane of the eyepiece two spider lines crossed at an angle of 60°, and the intersection of the cross-hairs was brought alternately from above and from below to what appeared to be the middle of the band. At least four settings were made on every band and two settings on the edge of the strip. In this way the height of each voltage and zero band above the edge of its strip was found at six and sometimes seven places of known wavelength varying from 5890 to 4180 Ångström units, — the wave-lengths being known from the cadmium reference spectrum and the strong carbon bands in the extreme violet. The negative was then inverted, each measurement repeated, and the mean taken to eliminate possible partiality for settings to the upper or lower side of the field of view. How accurately these settings ran may be seen from the following measurements of one plate, — the worst (Tables II and III). How accurately they *can* be made is shown in Table IV, — perhaps the best.

In spite of these precautions, reduction and comparison of the measurements of eight voltage bands show small discrepancies in the total shift, x, probably due, at least in part, to inaccuracies in the vertical ways on which the telescope was moved. Discrepancies of 0.2 mm., the largest found, might be caused by a very small tilt in the telescope,

TABLE II.

One Set of Measurements in Detail.

Negative, Erect, of Experiment 8. Temp. of CS_2, 22°.5.

Object viewed.	Telescope Scale Reading.						Volts.	Compensator Screw.
	λ 4216	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890		
	cm.	cm.	cm.	cm.	cm.	cm.		Turns.
First zero band	6.286	6.298	6.322	6.312	6.324	6.332		
	300	310	30	30	36	44		
	296	298	18	24	28	26		
	304	304	34	36	44	52		
						32		
						26		
Mean	6.297	6.303	6.326	6.326	6.333	6.335		
Edge of strip	6.040	6.046	6.058	6.062	6.064	6.066		
	40	48	60	66	66	68		
Mean	6.040	6.047	6.059	6.064	6.065	6.067		
Difference, or height of band	0.257	0.256	0.267	0.262	0.268	0.268	0	5.000
Voltage band	4.864	4.782	4.700	4.648	4.576	4.550		
	80	86	08	50	96	62		
	62	78	02	42	86	46		
	80	94	10	58	96	54		
Mean	4.872	4.785	4.705	4.650	4.589	4.553		
Edge of strip	3.802	3.824	3.834	3.848	3.850	3.862		
	04	26	36	50	52	64		
Mean	3.803	3.825	3.835	3.849	3.851	3.863		
Difference	1.069	0.960	0.870	0.801	0.738	0.690	8890	30.000
Second zero band	2.296	2.308	2.324	2.350	2.346	2.348		
	302	22	24	50	46	60		
	294	08	28	40	36	34		
	304	24	30	46	50	50		
Mean	2 299	2.316	2.327	2.347	2.345	2 348		
Edge of strip	1.612	1.618	1.626	1.632	1.628	1.640		
	16	20	30	38	28	40		
Mean	1.614	1.619	1.628	1.635	1.628	1 640		
Difference	0.685	0.697	0.699	0.712	0.717	0.708	0	0.000
	4216	4415	4677	5085	5378	5890	Wave-length checked.	

TABLE III.

TOTAL SHIFT, x_λ.

Summary of Table II and of two similar tables of measurements upon the negative, erect or inverted, of Experiment 8. Temp. of CS_2, 22°.5.

	Height of Zero and Voltage Bands.						Volts.	Compensator Screw.
	λ 4216	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890		
	cm.	cm.	cm.	cm.	cm.	cm.		Turns.
Negative Erect	0.257	0.256	0.267	0.262	0.268	0.268		
" Inverted	0.259	0.262	0.262	0.267	0.269	0.267		
" Erect					0.282	0.273		
(1) Mean height of first zero band	0.258	0.259	0.265	0.265	0.273	0.269	0	5.000
Negative Erect	1.069	0.960	0.870	0.801	0.738	0.690		
" Inverted	1.053	0.995	0.890	0.814	0.769	0.700		
" Erect					0.743	0.686		
(2) Mean height of voltage band	1.061	0.978	0.880	0.808	0.750	0.692	8890	30.000
Negative Erect	0.685	0.697	0.699	0.712	0.717	0.708		
" Inverted	0.697	0.716	0.721	0.719	0.726	0.718		
" Erect					0.709	0.706		
(3) Mean height of second zero band	0.691	0.707	0.710	0.716	0.717	0.711	0	0.000
(2) – (1) = Apparent Shift	0.803	0.719	0.615	0.543	0.473	0.423		
Add for Comp.	2.32	2.32	2.32	2.32	2.32	2.32		25.000
Total x_λ at 8890 v.	3.123	3.039	2.935	2.863	2.793	2.743	8890	
Total x_λ at 8990 v. $= \frac{9090}{8890} \cdot x_\lambda =$	3.192	3.108	3.000	2.928	2.855	2.304	8990	

TABLE IV.

TOTAL SHIFT, x_λ.

Like Table III, this table is a summary of tables similar to II for negative of Experiment 4. Temp. of CS_2, 25°.9.

	Height of Zero and Voltage Bands.						Volts.	Compensator Screw.
	λ 4180	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890		
	cm.	cm.	cm.	cm.	cm.	cm.		Turns.
Negative Erect	1.372	1.364	1.363	1.370	1.364	1.363		
" Inverted	1.367	1.358	1.359	1.365	1.364	1.370		
" Erect	1.372							
(1) Mean height of first zero band	1.370	1.361	1.361	1.368	1.364	1.367	0	–5.000
Negative Erect	1.291	1.171	1.110	1.020	0.957	0.894		
" Inverted	1.268	1.171	1.109	1.012	0.955	0.901		
" Erect	1.265							
(2) Mean height of voltage band	1.275	1.171	1.110	1.016	0.956	0.898	8980	+30.000
Negative Erect	0.879	0.885	0.889	0.878	0.886	0.873		
" Inverted	0.869	0.873	0.880	0.881	0.887	0.875		
" Erect	0.872							
(3) Mean height of second zero band	0.873	0.879	0.885	0.880	0.887	0.874	0	0.000
(2) – (1) = Apparent Shift	–0.095	–0.190	–0.251	–0.352	–0.408	–0.469		
Add for Comp.	3.14	3.14	3.14	3.14	3.14	3.14		35.000
Total x_λ at 8980 v. (Sensibly unchanged at 8990 v).	3.045	2.950	2.889	2.788	2.732	2.671	8980	

which was mounted four feet from the negative (120 cm.). A fixed telescope with micrometer eyepiece is being mounted, and will eliminate this uncertainty in future.

The difference between the positions of the voltage and zero bands gives the apparent shift, — that part of the total amount not taken up by changing the setting of the compensator. The reading of the compensator was reduced to terms of the apparent shift by photographing the zero bands for two settings of the compensator differing by from five to ten turns of the screw, the range being limited by the field of view. Thus it was found that for thirty turns, 2.73 cm. must be added to the apparent shift to get the total shift, x. The values of x obtained from the eight voltage bands thus far observed are recorded in Table V.

TABLE V.

Total Shift, x_λ, at 8990 Volts.

Summary of Tables III, IV, and similar ones, each for one experiment.

Exp.	Temp. of CS_2	Total observed shift, x_λ, at temperatures given, reduced to 8990 volts, or 56,000 volts per cm.						
		λ 4180	λ 4216	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890
No.	C	cm.	cm.	cm.	cm.	cm.	cm.	cm.
1	24°.3		2.922	2.831	2.744	2.647	2.589	2.529
4	25°.9	3.045		2.950	2.889	2.788	2.732	2.671
8	22°.5		3.192	3.108	3.000	2.928	2.855	2.804
2	9°.2	3.040	3.010	2.907	2.833	2.760		2.656
3	10°.9	2.992		2.900	2.835	2.760	2.692	2.620
5	11°.9	3.240		3.160	3.087	3.005	2.936	2.907
6	11°.0	3.247	3.232	3.160	3.061	2.980	2.915	2.868
7	10°.4	3.256	3.242	3.158	3.069	2.973	2.917	2.856

Treatment of Data.

Before the true significance of these measurements can be brought out, allowance must be made for dispersion in the natural double refraction of the quartz compensator. When plane-polarized light passes through quartz, the extraordinary wave is retarded over the ordinary by δ cm., an amount equal to the thickness, e cm., of quartz traversed, times the difference between the refractive indices, $(\mu_\epsilon - \mu_\omega)$. In Babinet's compensator, since the optic axis in the second wedge is at right angles to that in the first, the wave retarded in the first wedge is accelerated in the second, and vice versa. Hence

$$\delta = (e - e')\ (\mu_\epsilon - \mu_\omega),$$

With plane-polarized light the dark central fringe occurs where $\delta = 0$, namely, where the thickness of the first wedge, e, is equal to the thickness of the second, e'. This is the zero position. But when the incident light has already undergone double refraction, the central dark fringe will be shifted x cm. from the zero position to that point where the separation δ of the compensator is equal and opposite to the separation produced by the doubly refracting substance under observation. If i be the acute angle of the compensator wedges,

$$(e - e') = 2\,x \tan i$$

and at this point the separation due to the compensator is

$$\delta = 2\,x \tan i \cdot (\mu_\epsilon - \mu_\omega)$$

Since δ, x, and $(\mu_\epsilon - \mu_\omega)$ all vary with the color of the light, and since $(\mu_\epsilon - \mu_\omega)$ here refers to quartz, it is better to write the last equation with the subscripts λ, and Q, thus, (for quartz)

$$\delta_\lambda = 2\,x_\lambda \tan i \cdot (\mu_\epsilon - \mu_\omega)_{(\lambda,\,Q)}$$

In carbon bisulphide, in which $\mu_\epsilon > \mu_\omega$

$$\delta_\lambda = l \cdot (\mu_\epsilon - \mu_\omega)_{(\lambda,\,CS_2)}$$

at a given temperature, and given strength of electric field. In the voltage band the central fringe appears shifted by just the amount x_λ necessary to cause the compensator to counteract the separation induced by the electric field; or, stated algebraically,

$$\delta_\lambda = l \cdot (\mu_\epsilon - \mu_\omega)_{(\lambda,\,CS_2)} = 2\,x_\lambda \tan i \cdot (\mu_\epsilon - \mu_\omega)_{(\lambda,\,Q)} \qquad (1)$$

For sodium light, $\lambda = D$ and (1) becomes

$$\delta_D = l \cdot (\mu_\epsilon - \mu_\omega)_{(D,\,CS_2)} = 2\,x_D \tan i \cdot (\mu_\epsilon - \mu_\omega)_{(D,\,Q)} \qquad (2)$$

By dividing the first of these equations by the second, the double refraction in CS_2 for any wave-length can be expressed in terms of the double refraction for D light, $= (\mu_\omega - \mu_\epsilon)_{(D,\,CS_2)}$, as standard:

$$\frac{\delta_\lambda}{\delta_D} = \left[\frac{(\mu_\epsilon - \mu_\omega)_\lambda}{(\mu_\epsilon - \mu_\omega)_D}\right]_{CS_2} = \frac{x_\lambda}{x_D}\left[\frac{(\mu_\epsilon - \mu_\omega)_\lambda}{(\mu_\epsilon - \mu_\omega)_D}\right]_Q \qquad (3)$$

The values of $\left[\frac{(\mu_\epsilon - \mu_\omega)_\lambda}{(\mu_\epsilon - \mu_\omega)_D}\right]_Q$ are given in Table VI, which was made from data published by Macé de Lépinay in 1892 on the values of $(\mu_\epsilon - \mu_\omega)_{(\lambda, Q)}$.[20]

TABLE VI.

Dispersion Factor of Quartz.

The first line is obtained by interpolation from determinations by Macé de Lépinay, Jour. de Phys., (3) 1, 31 (1892).

The second line is calculated from the first.

	λ 4180	λ 4216	λ 4415	λ 4677	λ 5085	λ 5378	λ 5890
$(\mu_\epsilon - \mu_\omega)_{(\lambda, Q)}$	0.00951	950	943	936	926	921	913
$\left[\frac{(\mu_\epsilon - \mu_\omega)_\lambda}{(\mu_\epsilon - \mu_\omega)_D}\right]_Q$	1.042	1.041	1.033	1.025	1.014	1.009	1.000

Differences between different plates, thus far unexplained, are eliminated by using equation (3) in which the *ratio* of the observations to one of their own number, $\frac{x_\lambda}{x_D}$, is formed for each photograph, instead of placing values of x_λ from different plates in comparison, as would be the case in using equation (1). The observations have all been reduced to one strength of electric field, that obtained with 8990 volts, but the actual voltages were very nearly this, so that the corrections resting on the law of squares are small. In this way the values of x_λ given in Table V have been treated by (3) and the resulting values of the double refraction, $(\mu_\epsilon - \mu_\omega)_{(\lambda, CS_2)}$, in terms of $(\mu_\epsilon - \mu_\omega)_{(D, CS_2)}$ as one hundred per cent, have been tabulated and plotted near the beginning of this paper (Table I, and Figure 1).

Jefferson Physical Laboratory,
Harvard University.

---

[20] Jour. de Phys., (3) **1**, 31 (1892).

EXPLANATION OF PLATE.

FIGURE A. IRON SPECTRUM THROUGH CS_2, AND DIRECT.

The upper spectrum, taken through 96 cm. of the liquid, shows the rapidly increasing absorption of carbon bisulphide in the extreme violet. The lower spectrum was taken direct.

FIGURE B. ELECTRODES. — Silvered glass bars wedged face to face ready to be used as condenser electrodes.

FIGURE C. TYPICAL PHOTOGRAPHIC OBSERVATION SHOWING DISPERSION IN THE ELECTRIC DOUBLE REFRACTION OF CARBON BISULPHIDE.

The dark line throughout each band is the central dark fringe crossing the slit of the spectroscope at right angles and produced by the Babinet compensator.

The amount by which this line is displaced from horizontal in the "Voltage Band" shows the excess of dispersion in the double refraction of carbon bisulphide over that of the quartz compensator.

Each band was taken with a different setting of the compensator screw, and with an exposure of about forty minutes.

The strong bright lines in the extreme violet are carbon lines from the arc.

The reference spectrum was produced by a cadmium spark and sodium flame with exposures of from one to three minutes.

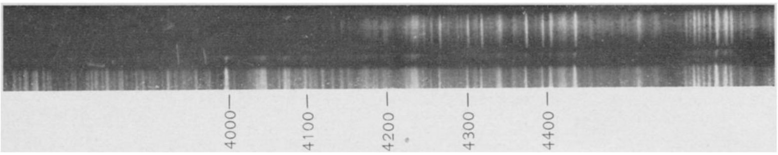

FIG. A.

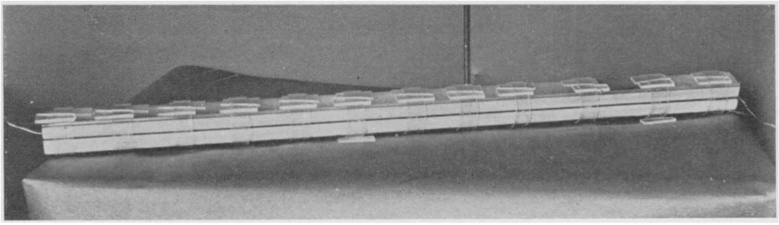

FIG. B.

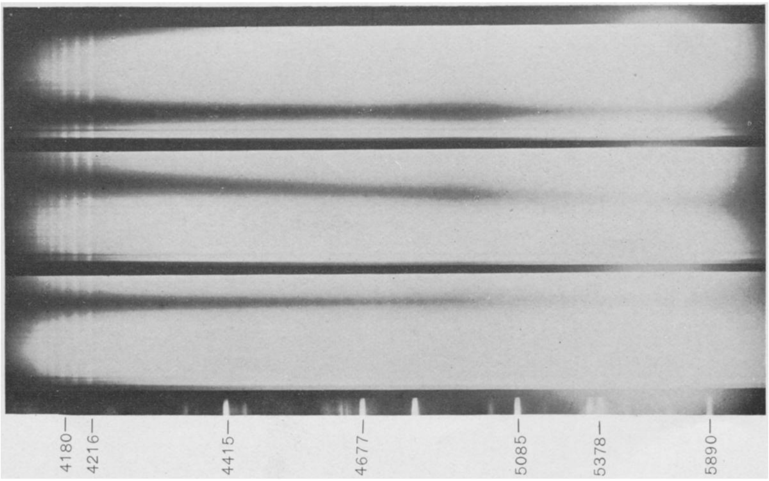

FIG. C.